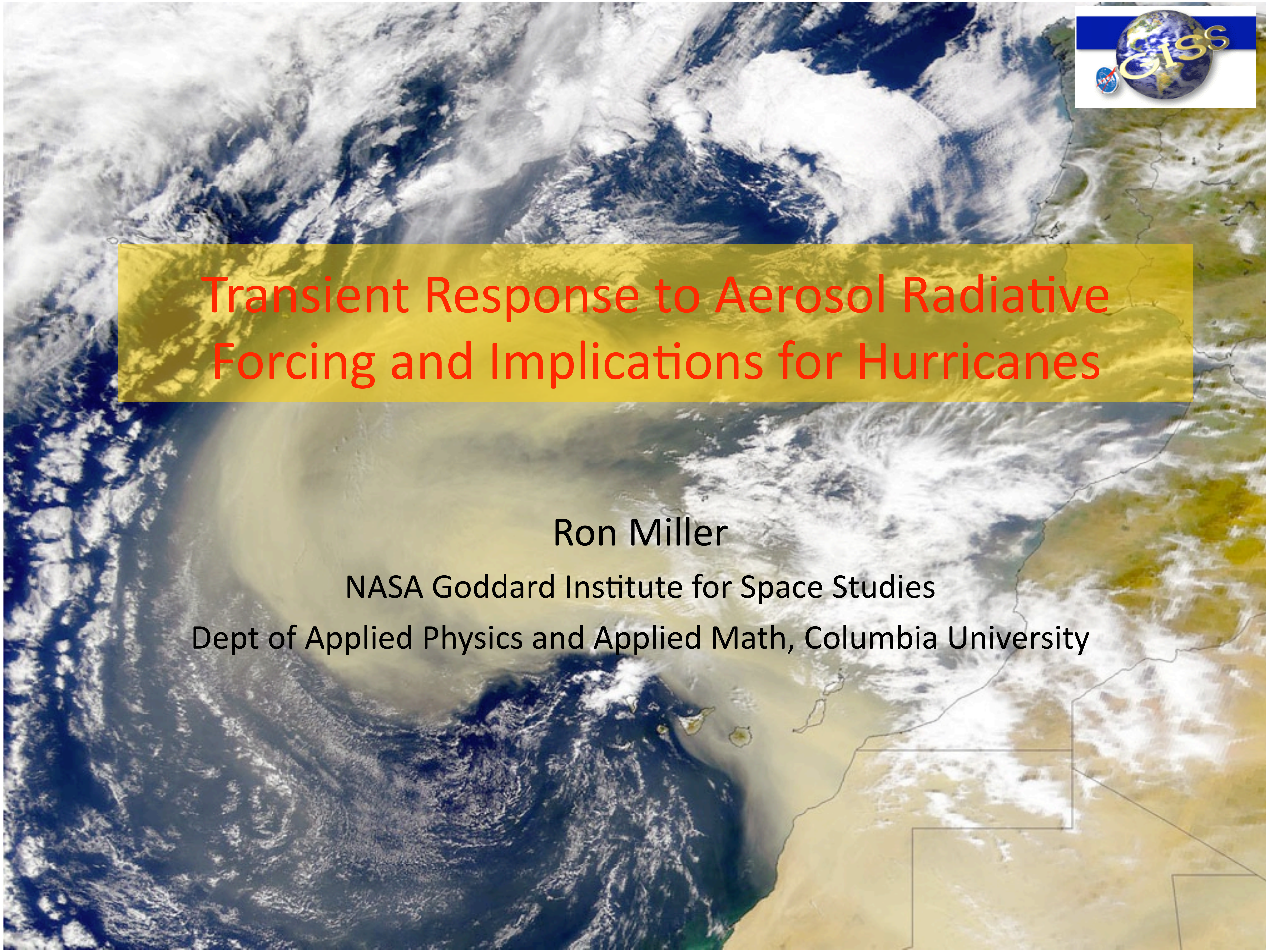

Transient Response to Aerosol Radiative Forcing and Implications for Hurricanes

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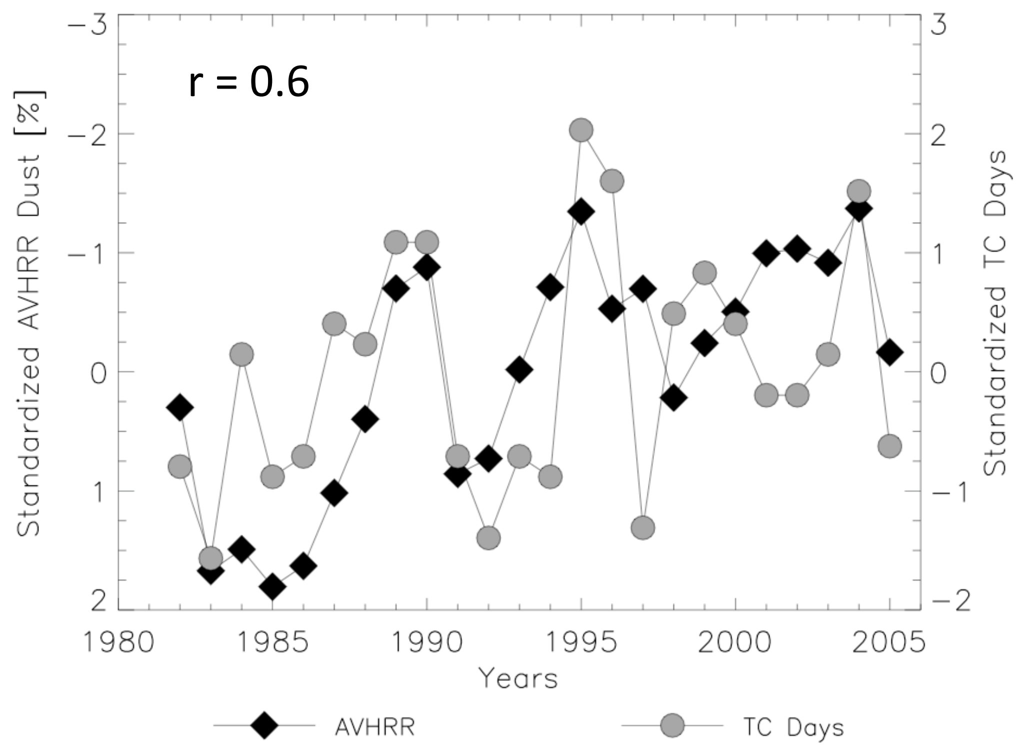
Anticorrelation of Dust Aerosols and Atlantic Hurricane Activity

- Robust anticorrelation of dust and hurricanes (Dunion and Velden 2004, Evan et al. 2006; Wong et al. 2008).
- Causal? Mechanism?
  - Intrusion of Dry Saharan Air Layer (Dunion and Velden 2004). Dust is passive?
  - Dust reduces SST (Lau and Kim 2007, Evan et al. 2007, Evan et al. 2008). How to quantify?



Evan et al. *Geophys. Res. Lett*. 2006

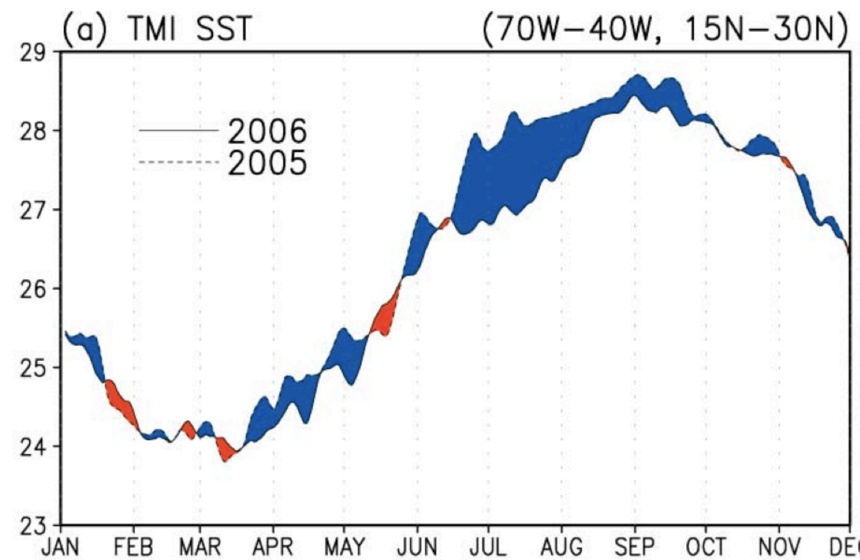
SST Adjustment to Dust Radiative Forcing

- SST (T_o') is typically calculated according to:

$$\rho h C_{p,o} \frac{\partial T_o'}{\partial t} = F_{Surf}$$

- Restoration of SST by surface fluxes (red) is neglected, assuming that SST adjusts quickly compared to surface flux time scale (a few months).

$$\rho h C_{p,o} \frac{\partial T_o'}{\partial t} = F_{Surf} + k(T_a' - T_o')$$



Lau and Kim *Eos* 2007

⇒ Does the air-sea heat flux and coupling with the atmosphere change the adjustment of SST?

Simple Model of Coupled Atmosphere and Ocean

- After Schopf *J. Phys. Ocean.* 1983:

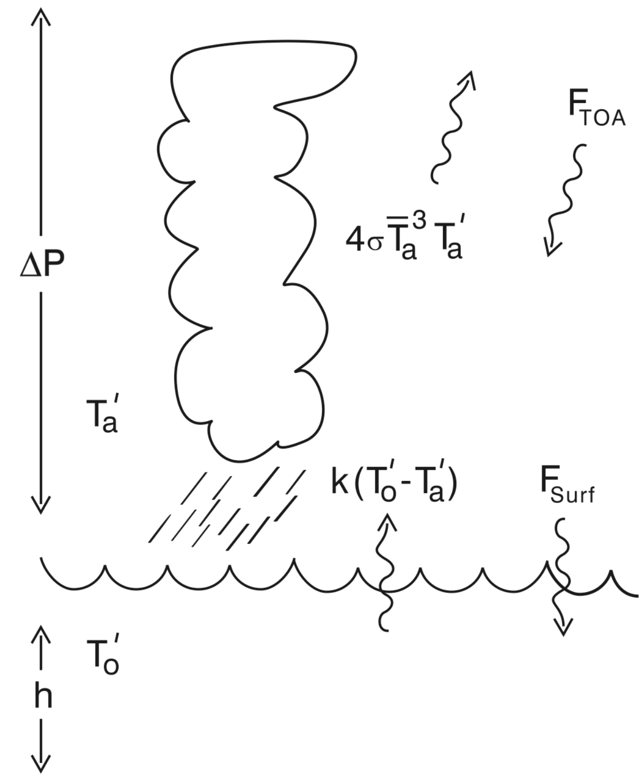
$$\rho h C_{p,o} \frac{\partial T_o'}{\partial t} = F_{Surf} + k(T_a' - T_o')$$

$$\frac{\Delta P}{g} C_{p,a} \frac{\partial T_a'}{\partial t} = F_{TOA} - F_{Surf} + k(T_o' - T_a') + 4\sigma \bar{T_a}^3 T_a'$$

- Note:
  - Tendency of T_a’ depends upon F_{TOA} in addition to F_{Surf},
  - The ocean has much larger inertia than the atmosphere.

- Equilibrium Solution:

$$\boxed{T_a' = aF_{TOA},\ T_o' - T_a' = bF_{Surf}}$$



⇒ Surface air temperature T_a’ is controlled by F_{TOA}. (Cess et al. *J. Geophys. Res.* 1985)

Key assumption: convective mixing maintains lapse-rate despite cooling beneath the aerosol layer.

Adjustment By Two Coupled Modes

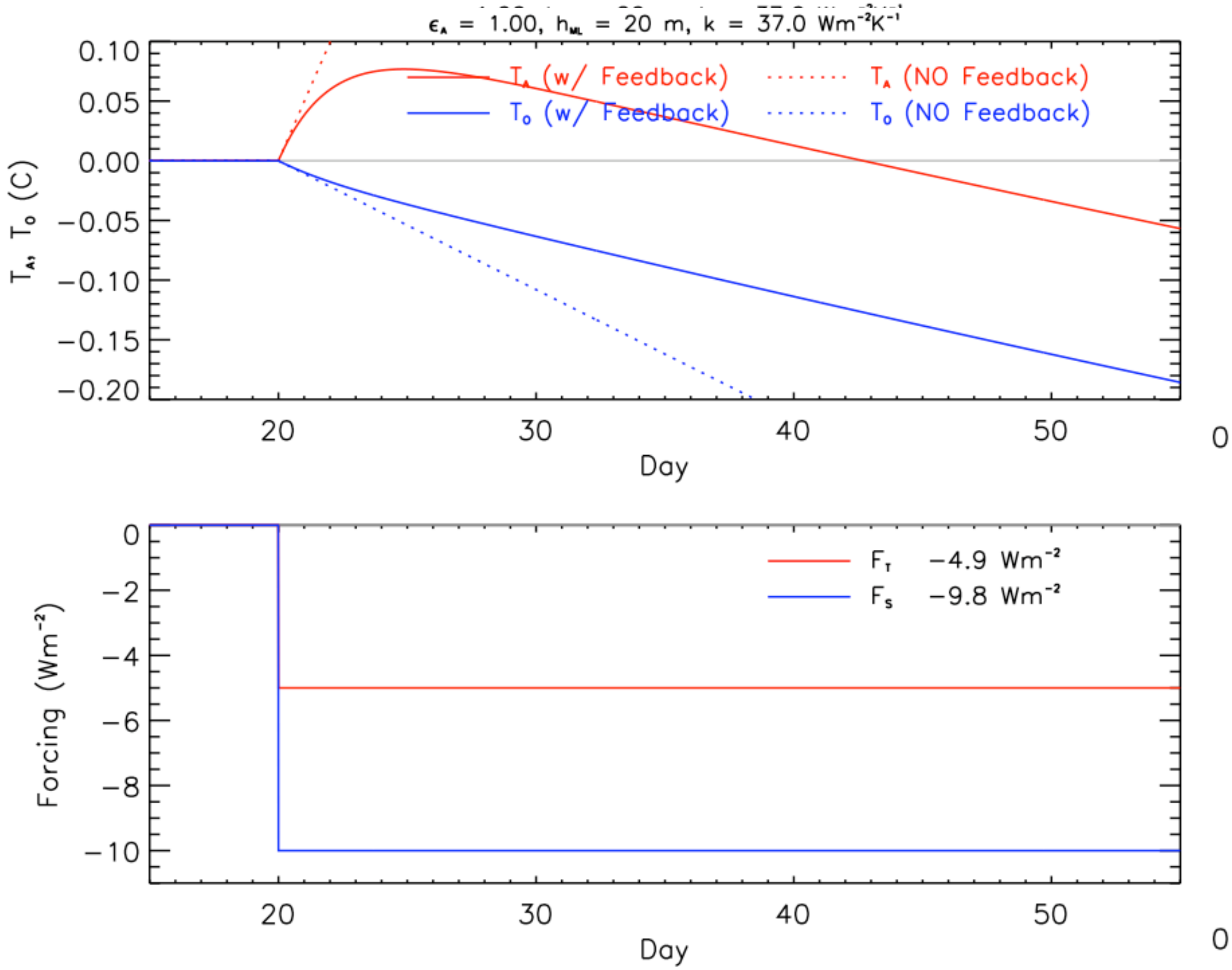
Time-dependent solution consists of equilibrium solution plus two transient modes ('eigenmodes' of the unforced equations).

$$\rho h C_{p,o} \frac{\partial T_o'}{\partial t} = F_{Surf} + k(T_a' - T_o')$$

$$\frac{\Delta P}{g} C_{p,a} \frac{\partial T_a'}{\partial t} = F_{TOA} - F_{Surf} + k(T_o' - T_a') + 4\sigma \bar{T}_a{}^3 T_a'$$

Slow Mode (few years): the atmosphere is in quasi-equilibrium with the ocean and both adjust slowly to the TOA aerosol forcing.
Fast Mode (a week): the atmosphere quickly warms by radiative absorption within the aerosol layer. This decreases the air-sea temperature difference, reducing the flux of heat from the ocean to the atmosphere. This opposes the cooling of the ocean by the aerosol surface forcing.

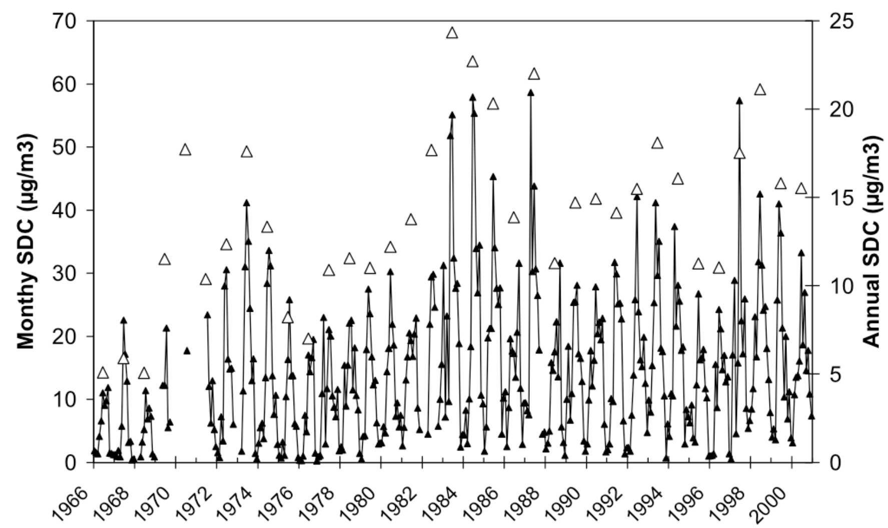
Example: Adjustment to Steady Forcing



Why Don't Aerosols Change SST Very Much?

- Surface Aerosol Forcing is opposed by heat flux from the ocean to the atmosphere (which reduces the cooling by about half in this example).
- A season is short compared to the adjustment time scale (mainly determined by the mixed layer depth). Despite an especially dusty summer, the ocean doesn't have much time to cool.
- However, dust might contribute to interdecadal variations in hurricanes, because this time scale is long compared to the adjustment time scale.

Annual (open triangles) and monthly (black triangles) surface dust concentration measured at Barbados



Chiapello, Moulin, Prospero, *J. Geophys. Res.* 2005

Surface Temperature Over the East Atlantic

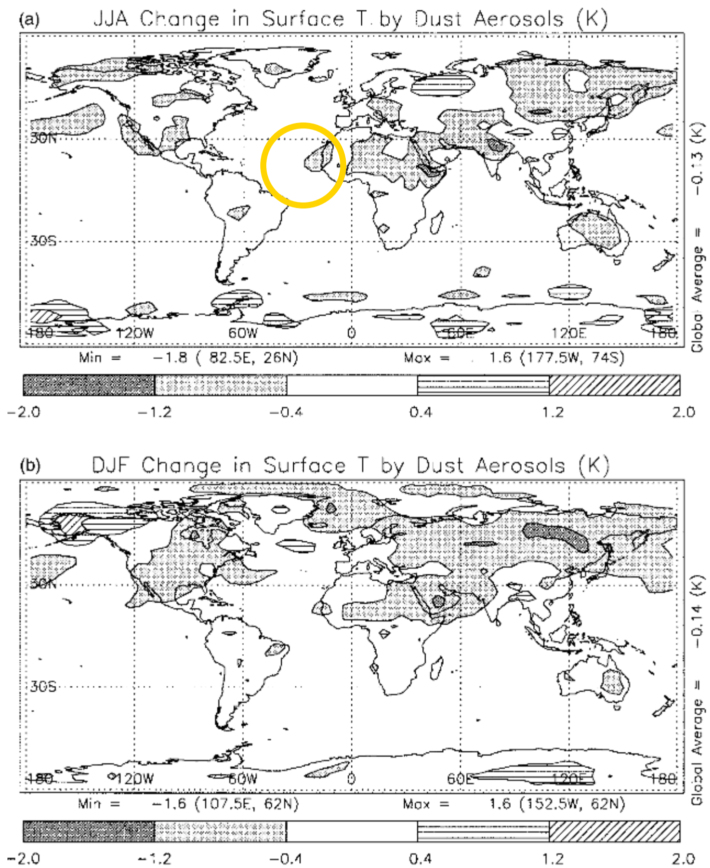


FIG. 5. Change in surface temperature (K) by soil dust aerosols for (a) JJA and (b) DJF.

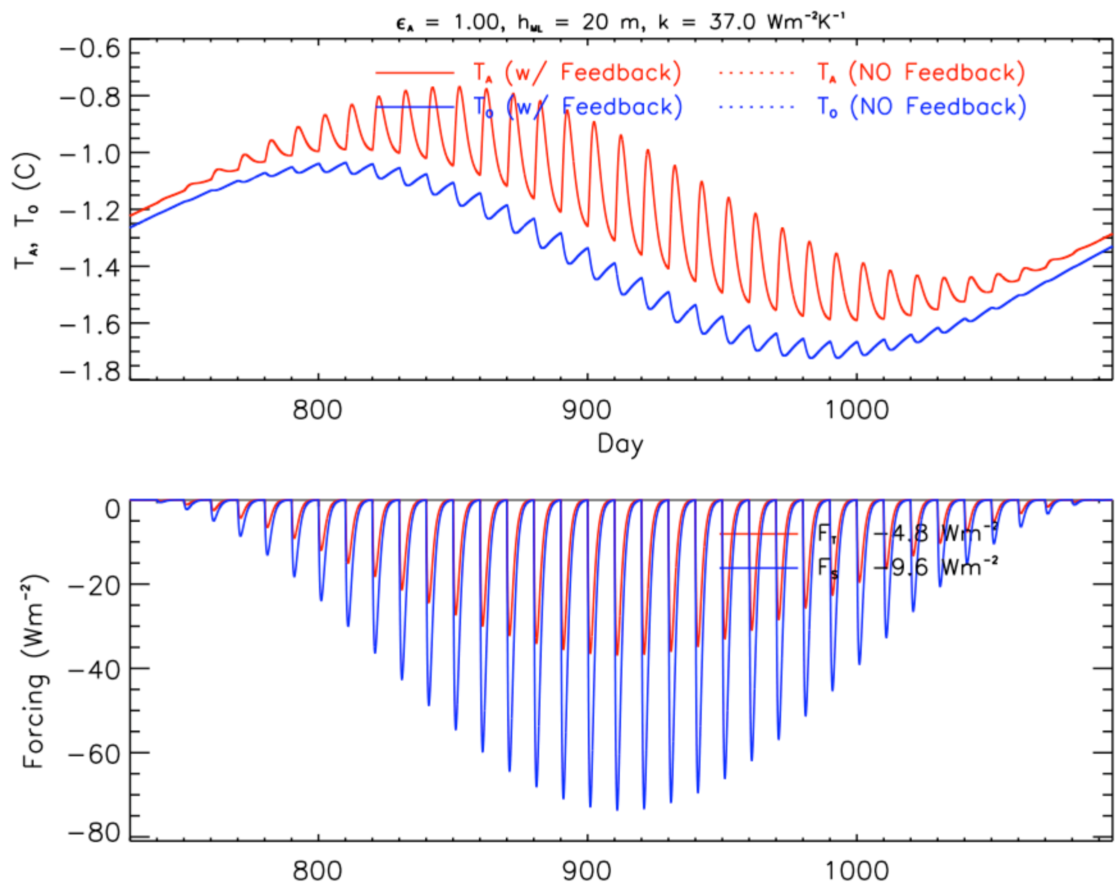
Miller and Tegen *J. Climate* 1998

Climatological reduction of surface air temperature is less than 1°C off the African coast, and is smaller downwind over the hurricane main development region.

Conclusions

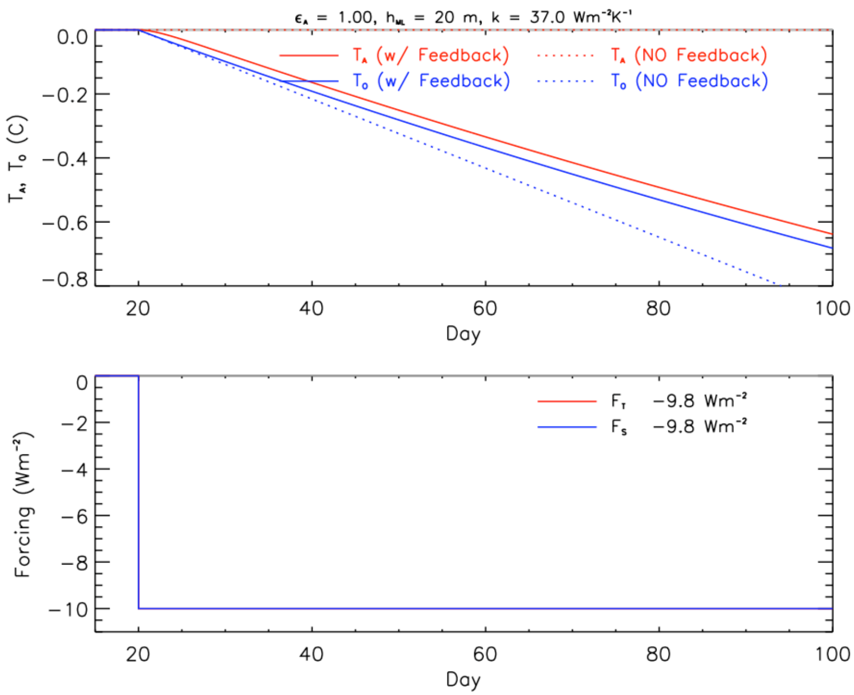
- T_a' adjusts to aerosol forcing along with T_o'. The atmosphere, which warms quickly in response to aerosol radiative heating, reduces the flux of heat from the ocean to the atmosphere, opposing cooling of the ocean by aerosol surface forcing.
- During a dusty summer, ocean cooling is about half of that predicted by holding atmospheric temperature fixed and not accounting for forcing at the top of atmosphere F_{TOA}. The cooling is limited by the slow (multi-year) response time of the ocean mixed layer temperature.
- On interdecadal timescales, where the climate can adjust fully to changes in dust radiative forcing, the cooling can be larger, although it should be calculated using both F_{TOA} and F_{SURF}.
- 3D Response: the atmosphere can moderate the local response to dust radiative forcing by changing lateral transport of energy away from the dust layer. (Need a better model with lateral dependence.)
- How does aerosol forcing change surface moisture or potential intensity, which is key to hurricane development?

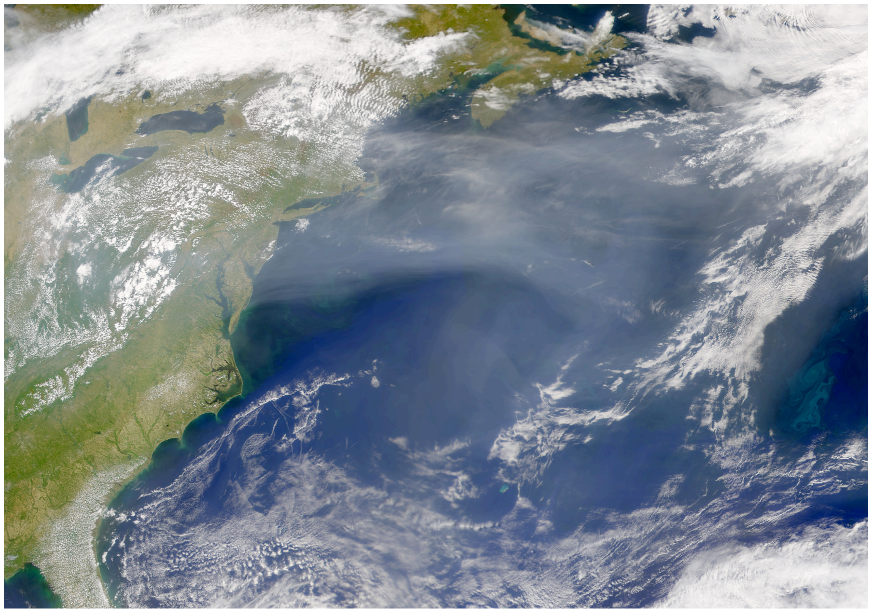
Example: Adjustment to Episodic Forcing



Cooling peaks a few months after the maximum dust forcing. The annual average cooling is related to the TOA forcing.

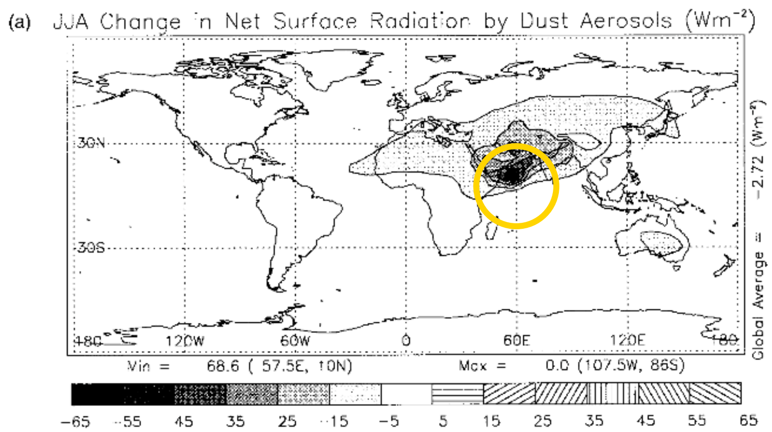
Reflective Aerosols and Hurricane Development

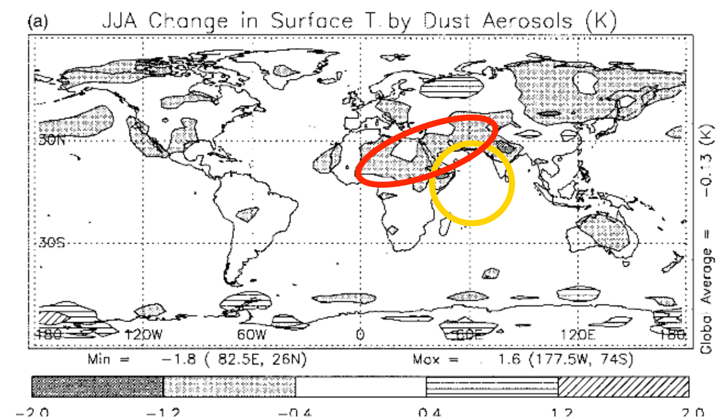




Unlike dust, sulfates do not warm by absorbing radiation, so cooling of the ocean through the surface heat flux is not reduced as much.

Surface Forcing and Surface Air Temperature





Miller and Tegen *J. Climate* 1998

⟹ Dust causes a large reduction of sunlight over the Arabian Sea (up to -55 Wm^{-2}), but surface air temperature is largely unchanged.

⟹ There is cooling on the fringes of the forcing (where precipitation is small and air subsides).

Lapse-rate Change By Aerosol Forcing

- Change is less than 1^{o}C over the depth of the troposphere (compared to the unperturbed value of 50^{o}C).

⇒ The column remains well-mixed despite the reduction in sunlight at the surface.

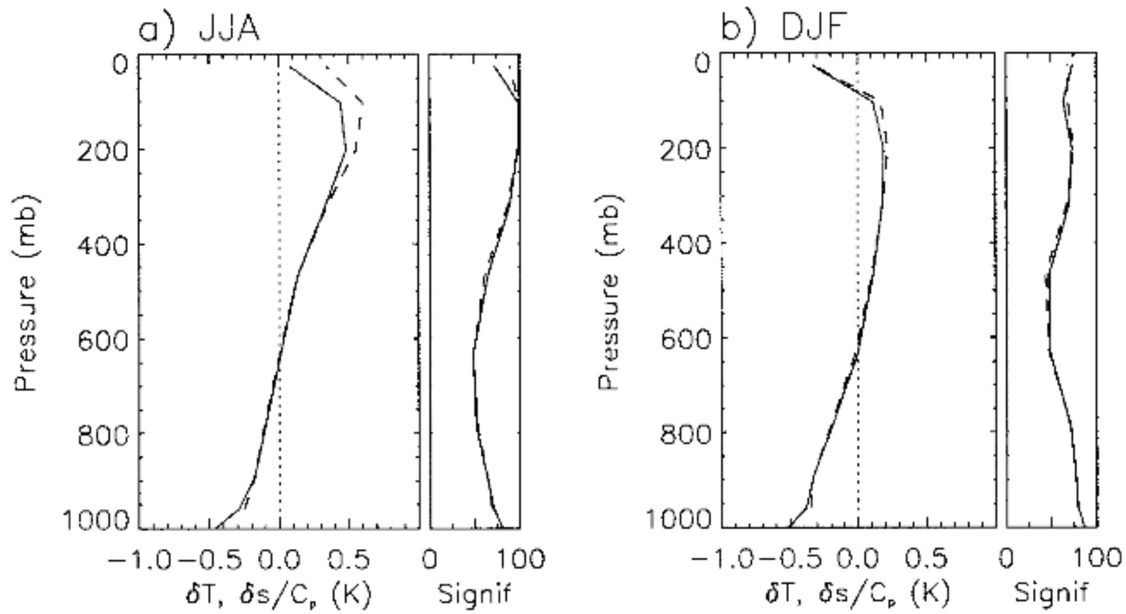


FIG. 4. Change in temperature (solid) and dry static energy (dashed, scaled by C_p) averaged over the extent of the dust cloud for (a) JJA and (b) DJF. The dust cloud is defined as the region where surface net radiation is reduced by at least 5 W m^{-2} in Fig. 1. "Signif" refers to the statistical significance of the anomalies, averaged over the extent of the dust cloud.

Miller and Tegen *J. Climate* 1998